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Technique for Selecting An Aerosol Model Useful for Infrared Atmospheric Transmittance Calculations

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Vertical profiles of meteorological parameters are used with the LOWTRAN 6 atmospheric transmittance/radiance computer code to model measurements of near horizon infrared radiances. It is shown that calculations with the Navy Maritime Aerosol Model can exactly reproduce the measured horizon pixel radiance using nonunique combinations of air mass factors and surface visibilities. This feature is the result of the visibility scaling factor of the size distribution remaining nearly constant for any appropriate combination of the two factors, and the relative insensitivity of the calculated extinction coefficients for the far infrared wavelengths to the air mass factor term. Using measurements taken on two consecutive days during low wind-speed conditions, it is shown that any appropriate combination of the two factors will allow the calculated and measured radiances at other angles above the horizon to differ less than 2%. These agreements place confidence in using the selected aerosol model in transmittance calculations for the far infrared wavelength bands over other propagation paths.

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SUMMARY

OBJECTIVE

In the absence of real time measurement of aerosol size distributions, develop a technique of selecting appropriate input parameters to an aerosol model, based on measurable meteorological parameters, which can be used in infrared transmittance calculations.

RESULTS

This study has shown that nonunique combinations of air mass factors and visibility allow an appropriate LOWTRAN 6 Navy Maritime Aerosol Model to be selected such that calculated and measured infrared horizon radiances agree.

RECOMMENDATIONS

Extend modeling effort to incorporate a near infrared Light Detection and Ranging (LIDAR) system with the infrared measurements to select an appropriate aerosol model for both the near and far infrared wavelength bands.

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FIGURES

TABLE

INTRODUCTION

In the absence of size distribution measurements, we must presently rely on the models in the LOWTRAN 6 (Kneizys, 1983) code to calculate the effects of aerosols on infrared (IR) atmospheric transmittances and background radiances using measured meteorological parameters as inputs. These aerosol models were developed to be as representative as possible of different atmospheric conditions. However, they cannot be expected to exactly reproduce the optical properties in a given location at any specific time. A method is needed for selecting the input parameters so that the model best represents a particular situation. Of particular interest to Navy applications, is the Navy Maritime Aerosol Model for use in electro-optical systems performance prediction codes.

This model (see Appendix) is the sum of three log normal-size distributions, and, in addition to the surface wind speeds (current and 24-hour averaged) and relative humidity, requires the input of an air mass factor which identifies the origin of the aerosols as either marine or continental which is allowed to range between integer values of 1 for open ocean conditions and 10 for coastal regions. Also, when an observed surface visibility is available as an input, the model is adjusted so that the visibility calculated at a wavelength of 0.55 μm is the same as the observed value. The accuracy to which this model can predict atmospheric transmission or radiance for a given wavelength band is sensitive to the selection of the appropriate visibility and air mass factor (Gathman, 1983). The air mass factor may be determined by either the measurement of atmospheric radon or by an air mass trajectory analysis to determine the time the air mass has been over land.

The second option is extremely difficult, and requires a large data set of synoptic flow patterns. Neither of these techniques are presently available for shipboard use. Also, radiance contrast measurements between the sky background and objects at known distances in the open ocean are rarely available, and visibilities inferred from point scattering measurements onboard ship are most apt to be contaminated by ship effluences.

In this paper, a remote sensing technique is presented whereby an appropriate aerosol size distribution model can be selected which is applicable to transmittance and radiance calculations in the far infrared wavelength bands. In this method, non-unique combinations of the air mass factor and visibility for different meteorological conditions are inferred from LOWTRAN 6 calculations which allow agreement with measurements of 8- to 12-μm horizon radiances.

MEASUREMENTS

For this study, a Piper Navajo aircraft, equipped with Rosemount temperature and pressure probes, and an EG&G dewpoint sensor, made vertical spirals over the ocean to obtain the profile of temperature, relative humidity and pressure which are required inputs to the LOWTRAN 6 computer code for calculating the sky radiances. The vertical profiles of temperature and relative humidity, measured at 1450 PST on 9 November and 1424 PST 10 November 1988 off the coast of San Diego, California, are shown in Figures 1 and 2, respectively. The current and 24 hour averaged wind speeds ($V_c = 3.7$ m/s and $\bar{V} = 2.1$ m/s for 9 November, and $V_c = 4.8$ m/s and $\bar{V} = 2.8$ m/s for 10 November) measured on shore during both days were from a westerly direction. At the time the meteorological parameters were obtained, measurements of IR (8- to 12-μm) horizon radiances were also made with a calibrated thermal imaging system (AGA THERMOVISION, model 780) using a 2.95° field-of-view lens.

For these measurements the scanner was located at an elevation of 33 m on the Point Loma peninsula in San Diego and was directed over the ocean in a southerly direction. The response of the system is determined by placing a blackbody of known temperature ($\pm$0.1°C for temperatures <50°C) in front of the lens aperture. The digitized video signal transfer function of the system then allows the blackbody temperature to be reproduced to within $\pm$0.2°C. The data processing software of the AGA system also allows the thermal scene to be displayed on a computer terminal in a format consisting of 128 pixels (0.023°/pixel). The effective blackbody temperature corresponding to each pixel can then be displayed on the screen by positioning a cursor at the appropriate position.

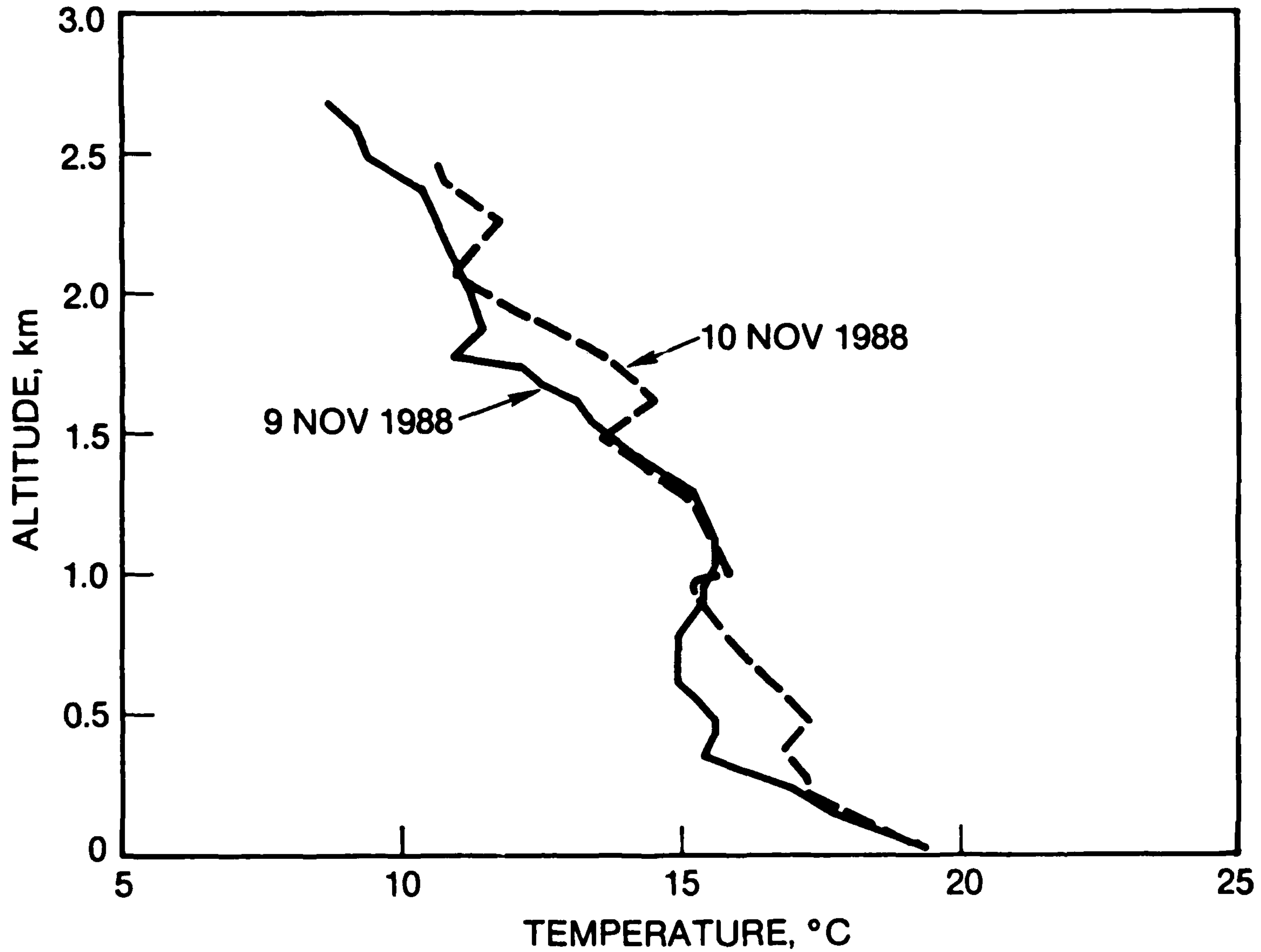

Figure 1. Profiles of air temperature measured with altitude on 9 and 10 November 1988 off the coast of San Diego, California.

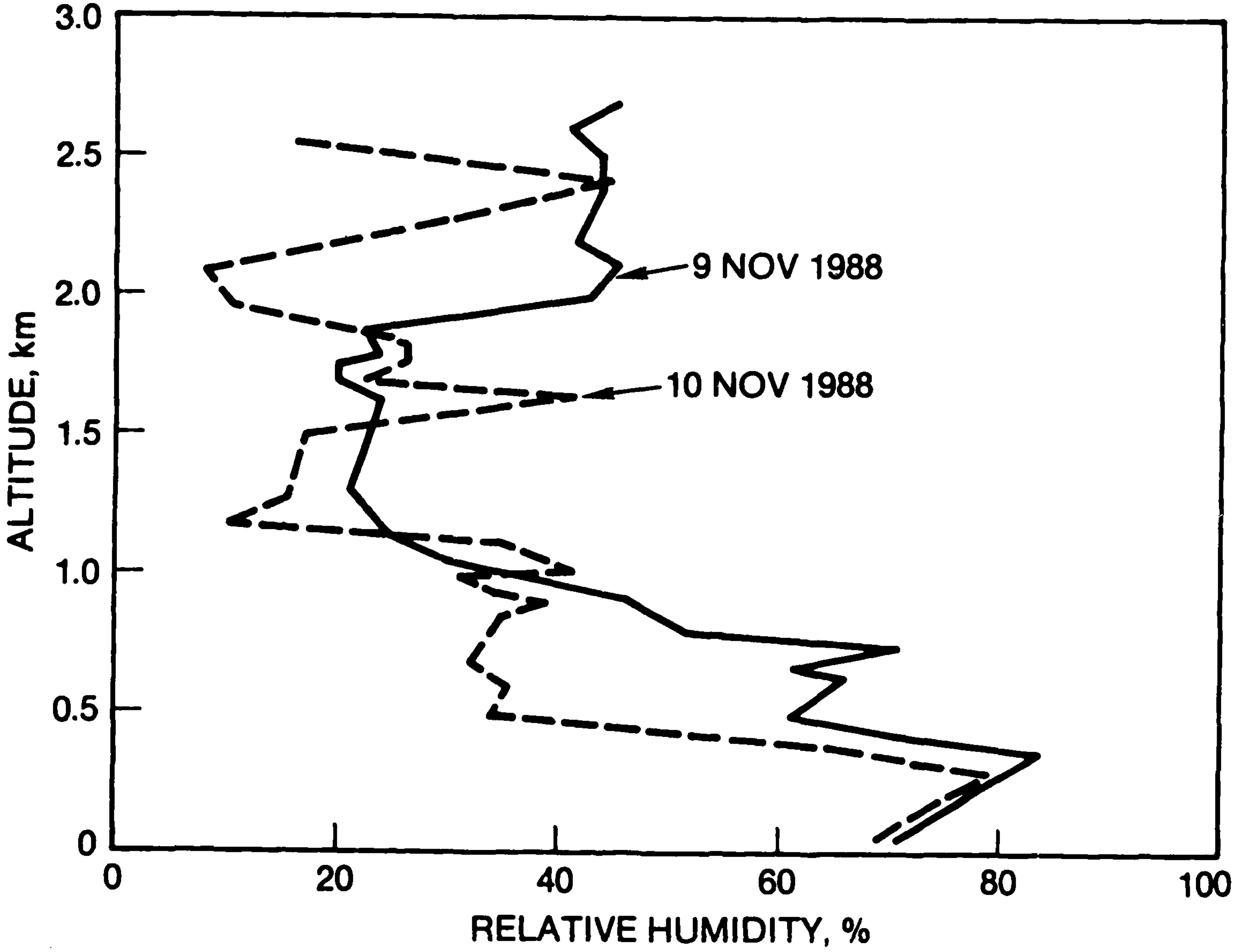

Figure 2. Profiles of relative humidity measured with altitude on 9 and 10 November 1988 off the coast of San Diego, California.

CALCULATION OF BACKGROUND RADIANCE SCENES

These measurements can be modeled with LOWTRAN 6 calculations to aid in selecting an appropriate aerosol model for radiance calculations on each day. In these calculations the meteorological profiles were divided into 33 layers as allowed by LOWTRAN 6. The lower layers of the profiles are also divided into sublayers containing the same amount of absorbing and scattering material and temperature as the original layer. This artificial layering has been found necessary (Wollenweber, 1988) to remove the anomalous dip (Hughes, 1987) which occurs when aerosols are included in the LOWTRAN 6 radiance calculations for zenith angles close to 90°.

As the AGA scanner could not be accurately plumbed, the zenith angle of the infrared horizon (the pixel corresponding to the maximum radiance) in each thermogram was taken to be one-half of a pixel less than the angle ($\theta = 90.177°$ on 9 November and $\theta = 90.175°$ on 10 November) for which the LOWTRAN calculations indicated the refracted ray path first struck the earth. Using these zenith angles with the measured profiles of meteorological parameters, the visibility required to match the measured horizon pixel radiance, for each integer value of air mass factor, must be determined by iteration from several different LOWTRAN calculations. The locus of points which allow the LOWTRAN calculations to exactly match the measured horizon pixel radiances (3.27 mW/cm^2 sr on 9 November and 3.281 mW/cm^2 sr on 10 November) with nonunique combinations of air mass factor and visibility for the two days are shown in Figure 3.

This feature is the result of the visibility scaling factor (see Appendix) of the size distribution remaining nearly constant for any appropriate combination of the two factors, and the relative insensitivity of the calculated extinction coefficients for the far infrared wavelengths to the air mass factor term (AM) as shown in Figure 4. Any appropriate combination of the two factors will allow the radiances calculated at other angles above the horizon to be nearly identical as seen in Figures 5 and 6. Using widely different combinations of air mass factors and visibilities as shown in the figures, the calculated and measured values for 9 November differ by less than 2% over an elevation angle of approximately 1°.

These radiance differences correspond to equivalent blackbody temperature differences of less than 0.7°C near the elevation angles of 0.4° and 0.8°. On 10 November the calculated and measured radiances with elevation are in excellent agreement below 0.8° elevation angle. Above that angle, the radiance differences amount to less than 0.5°C in equivalent blackbody temperature.

The variations in calculated transmittances (τ) to the infrared horizons (R_{hor} = 19.491 km on 9 November and R_{hor} = 18.073 km on 10 November), corresponding to the zenith angles where the refracted ray path first hit the earth, are shown in Figure 7 for the different combinations of air mass factor (AM) and required visibility. The resulting extinction coefficient (determined from the relation $\sigma = (-\ln\tau)/R_{hor}$ are shown in Figure 8. Both the calculated transmittances and resulting extinction coefficients show little variation for the different combinations of air mass factor and required visibility. These calculations are also summarized in Table 1. In the table, N_c, N_m, and V_r refer to the calculated and measured radiances, and required visibility, respectively.

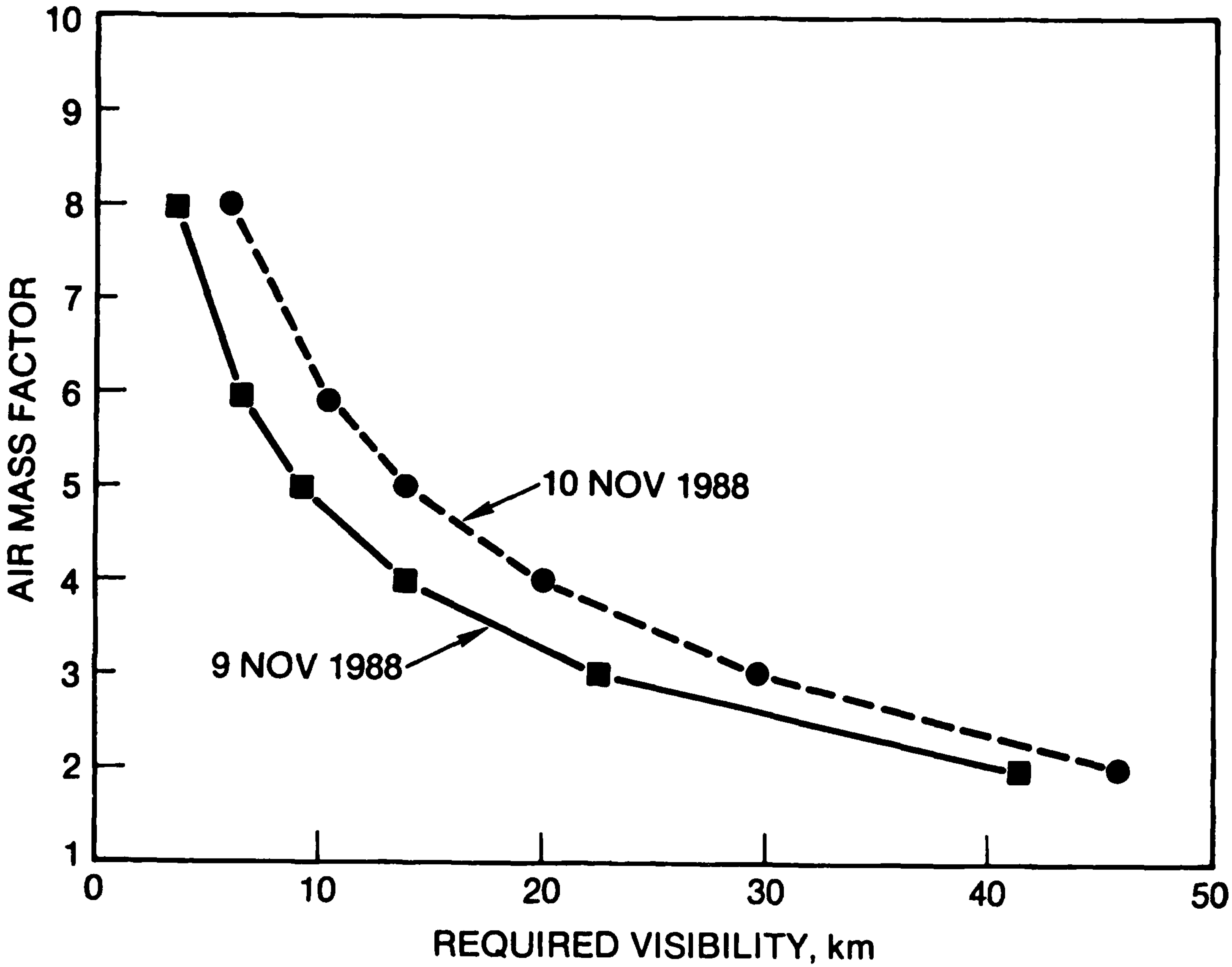

Figure 3. Loci of points of LOWTRAN 6 calculations with different combinations of air mass factors and visibilities which match measured values of IR (8- to12-μm) horizon radiances on 9 and 10 November 1988.

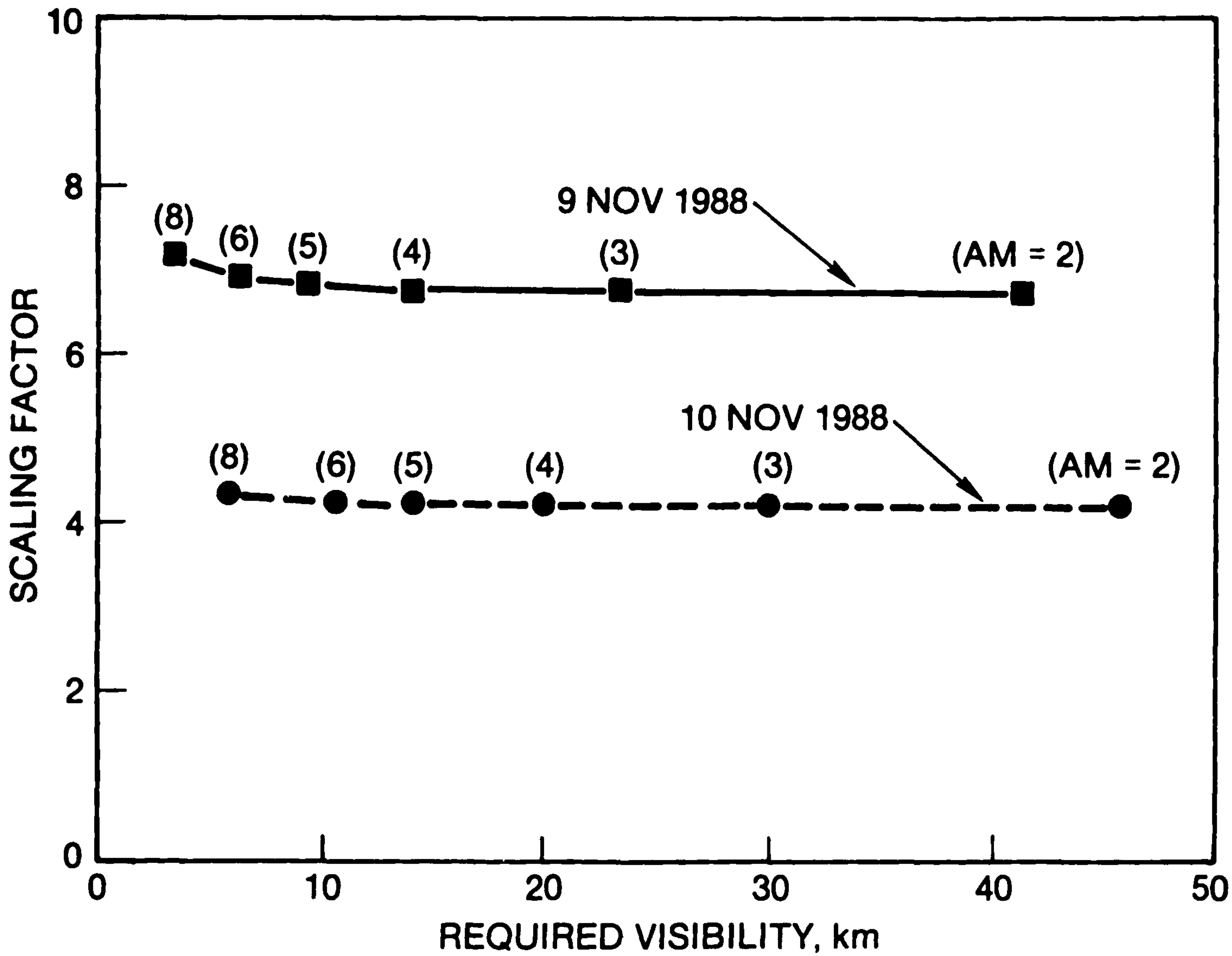

Figure 4. Aerosol size distribution scaling factor (SF) versus the required surface visibility to match the measured infrared horizon pixel radiance for fixed values of air mass factors (AM).

DISCUSSION

The results of this study have shown that in the absence of radon and visibility measurements, appropriate combinations of these two inputs to the Navy Aerosol Model can be inferred from LOWTRAN 6 calculations using standard meteorological inputs to match measured infrared horizon pixel radiances. In a practical sense, sophisticated instruments with the temperature resolution (0.1°C) and instantaneous field-of-view (0.87 mr) similar to the AGA would have to be mounted on stabilized platforms for shipboard use. Such instruments are not presently available. However, horizon radiance measurements with hand-held instruments with wider fields-of-view of 1° or better could possibly be matched by calculated radiances integrated over the instrument's field-of-view as demonstrated in figures 5 and 6.

The approach here is limited to the far infrared wavelengths. For shorter wavelengths the transmittances and extinction coefficients calculated with the model will depend more strongly on the air mass factor in the first component of the distribution. In earlier work (Hughes, 1988), it was demonstrated that an appropriate aerosol size distribution could be selected which is applicable to transmittance and radiance calculations in both the visible and IR wavelength bands by including calculations which also matched the visible atmospheric optical depths determined from satellite detected upwelling solar radiances. This approach, however, is limited to cloud-free sky conditions during the daytime and requires a favorable position of the satellite to avoid sun glint from the ocean. An alternative approach is to incorporate a visible or near-infrared LIDAR system with the infrared measurements and model the backscattered power as a function of range.

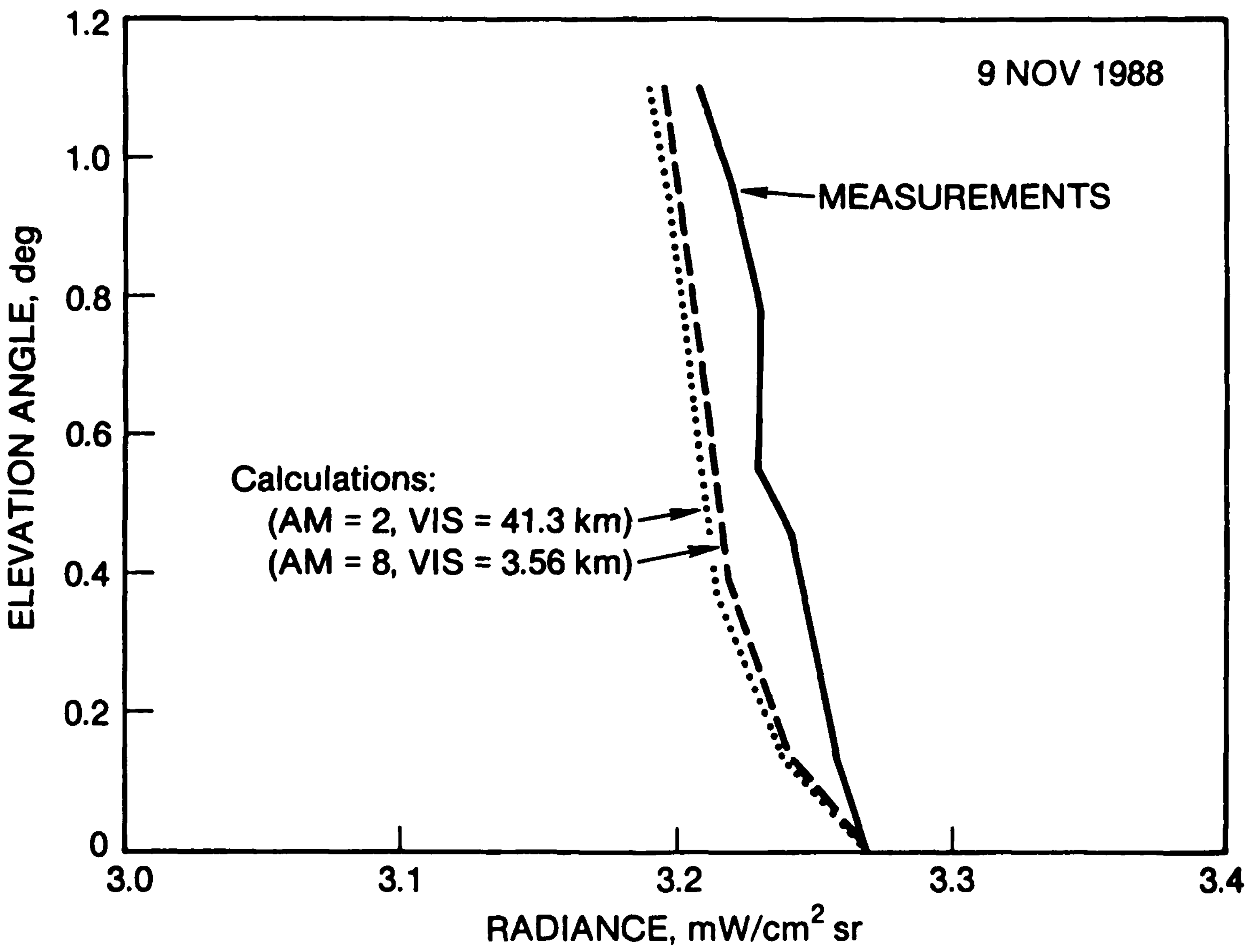

Figure 5. Comparison of the measured and calculated IR (8- to12-μm) radiances for zenith angles about 1° above the horizon using different combinations of air mass factors and visibilities determined for 9 November 1988.

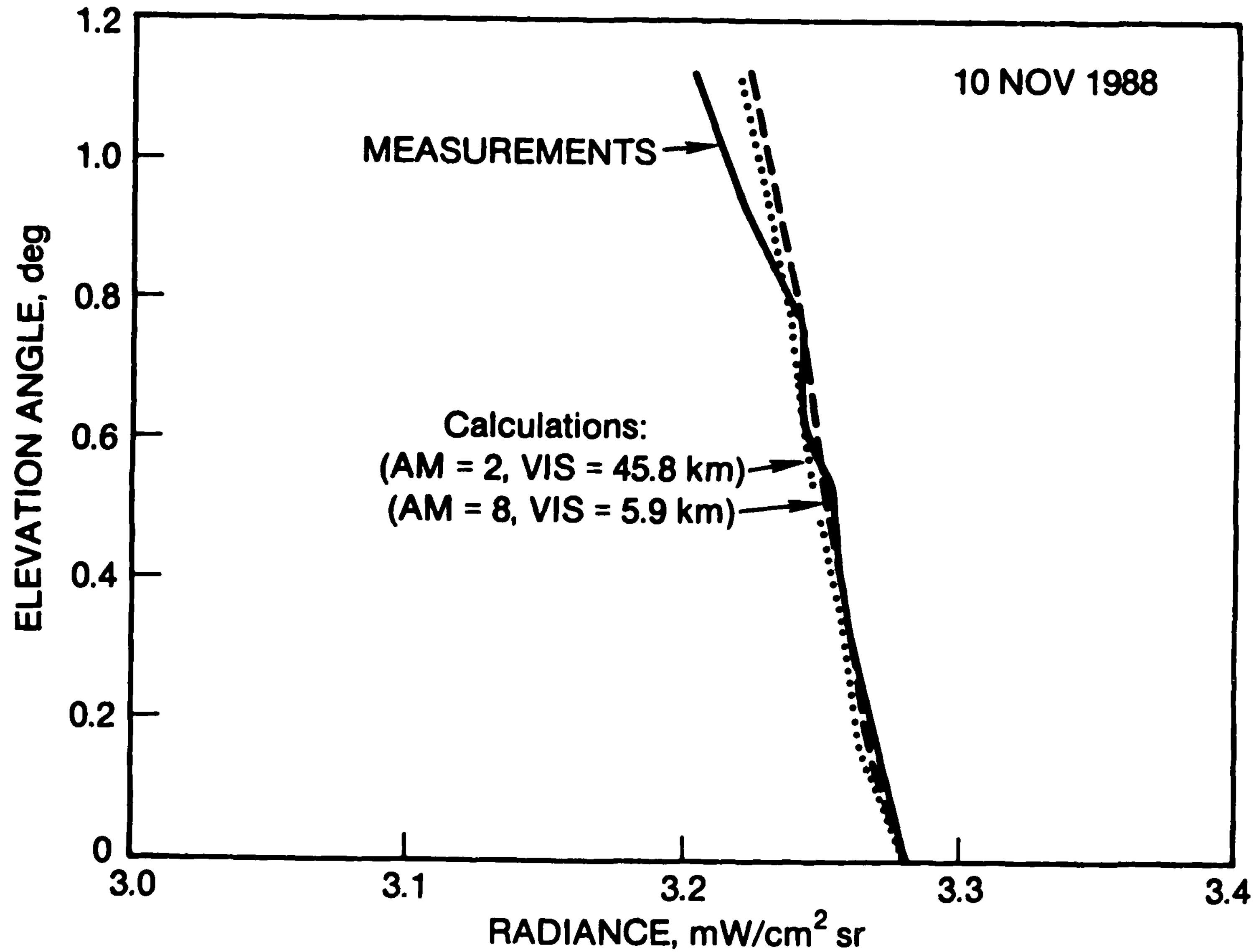

Figure 6. Comparison of the measured and calculated IR (8- to12-μm) radiances for zenith angles about 1° above the horizon using different combinations of air mass factors and visibilities determined for 10 November 1988.

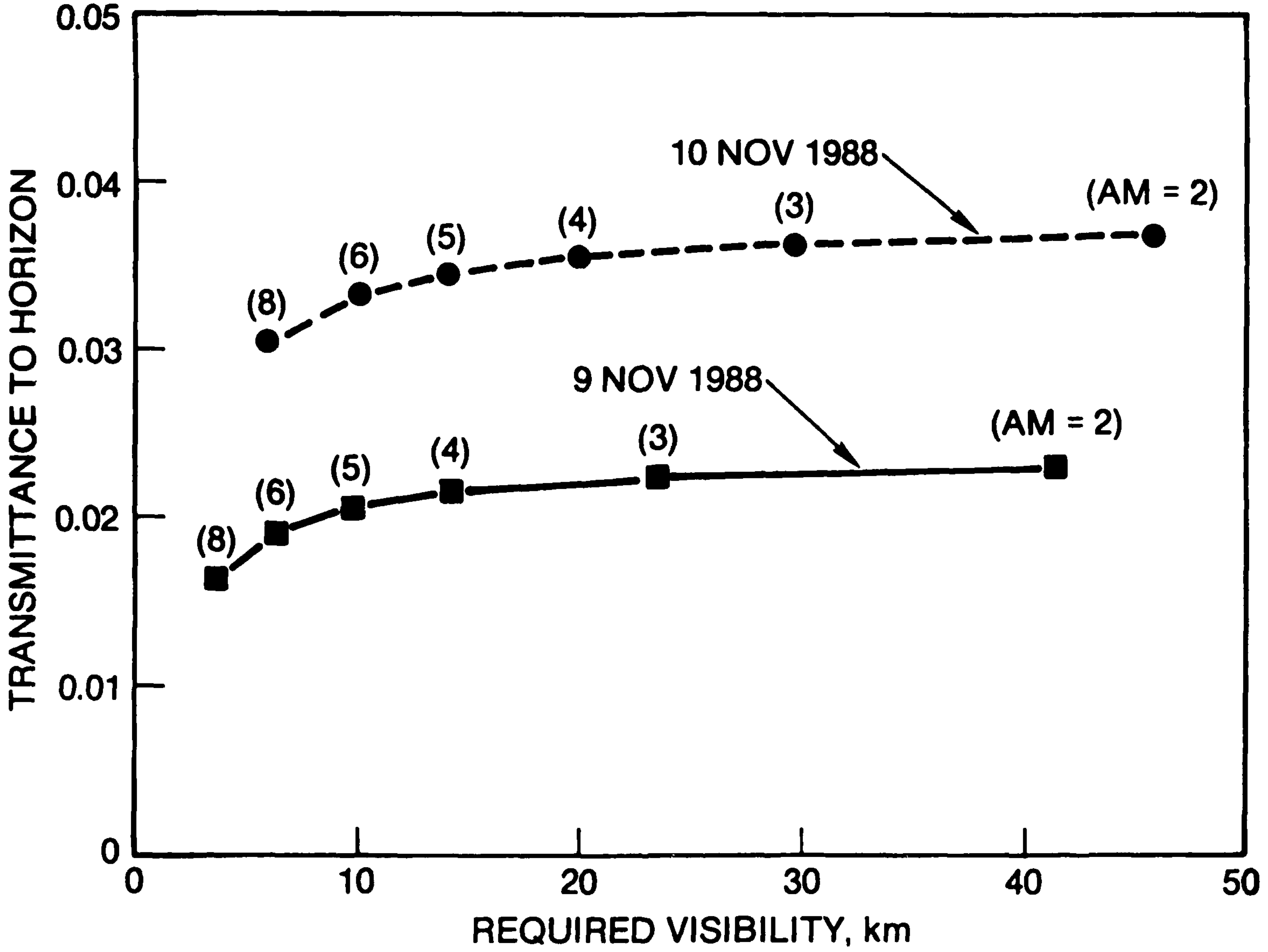

Figure 7. Calculated values of IR (8- to12-μm) transmittances to the horizon using different combinations of air mass factors (AM) and required surface visibility.

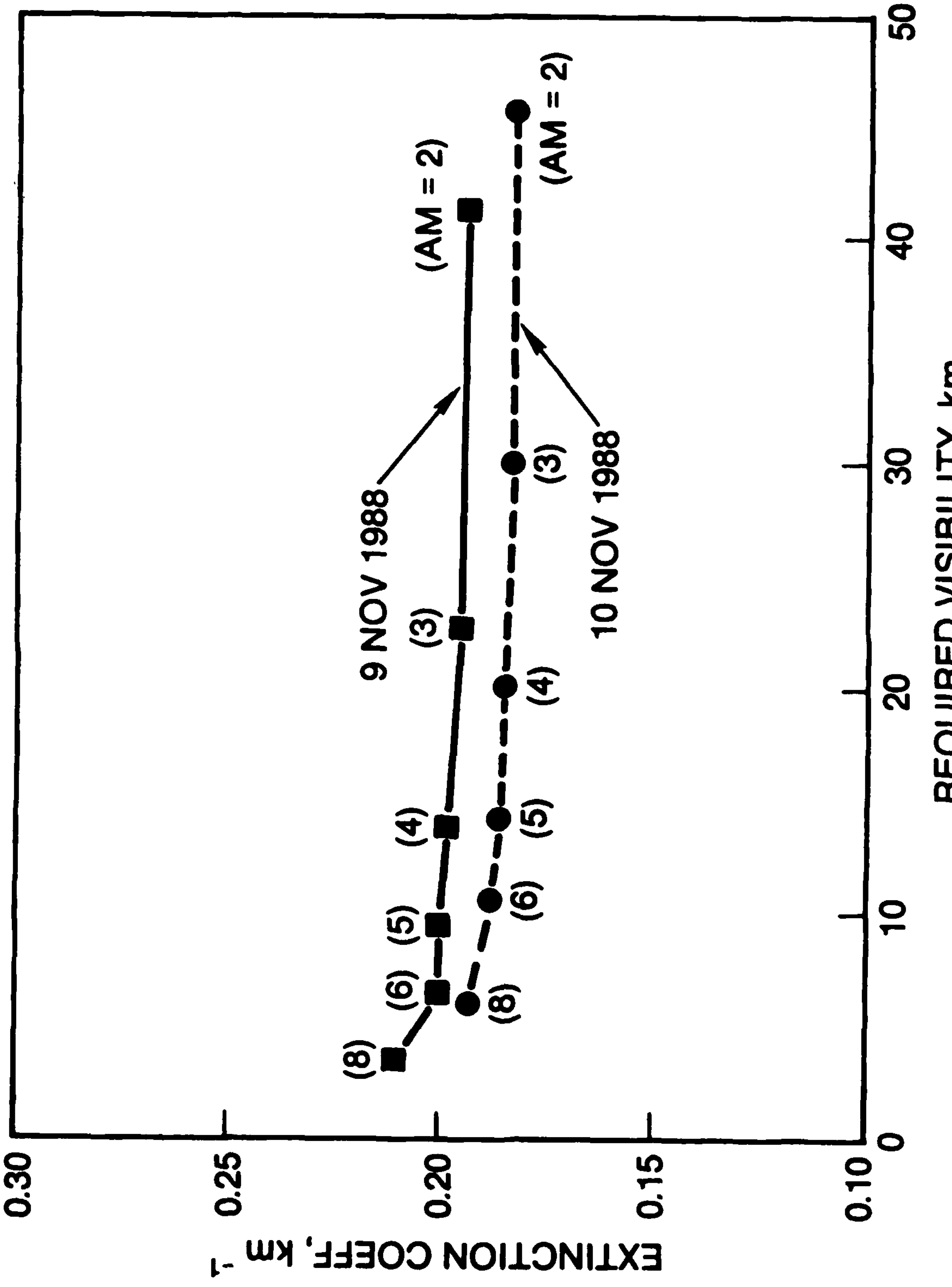

Figure 8. Extinction coefficients corresponding to the calculated transmittances shown in Figure 7.

Table 1. Summary of LOWTRAN 6 calculations of scaling factors, horizon pixel radiances, transmittances and extinction coefficients using different combinations of air mass factors and required surface visibilities.

	AM	V_r (km)	SF	N_c (mW/cm^2 sr)	τ	σ (km^{-1})
9 Nov 1988	2	41.3	6.71	3.270	0.023	0.194
N_m = 3.270 mW/cm^2 sr	3	22.5	6.75	3.270	0.022	0.195
R_{hor} = 19.491 km	4	13.8	6.74	3.270	0.021	0.198
	5	9.1	6.82	3.270	0.020	0.200
	6	6.4	6.89	3.270	0.019	0.200
	8	3.56	7.14	3.270	0.016	0.210
10 Nov 1988	2	45.8	4.16	3.281	0.037	0.183
N_m = 3.281 mW/cm^2 sr	3	29.6	4.18	3.281	0.036	0.183
R_{hor} = 18.073 km	4	19.8	4.19	3.281	0.036	0.185
	5	13.1	4.22	3.281	0.035	0.186
	6	10.1	4.22	3.281	0.033	0.188
	8	5.9	4.31	3.281	0.030	0.193

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APPENDIX A

DESCRIPTION OF THE LOWTRAN 6 NAVY MARITIME AEROSOL MODEL

DESCRIPTION OF THE LOWTRAN 6 NAVY MARITIME AEROSOL MODEL

Description of the particle size distribution model (at radius r) is the sum of three log-normal distributions given by

$$n(r) = \sum_{i=1}^{3} A_i \exp\left[- (\ln \frac{r}{fr_i})^2 \right] \qquad (cm^{-3}\ \mu m^{-1}), \tag{1}$$

where

$$A_1 = 2000(AM)^2 , \tag{2}$$

$$A_2 = 5.866\ (\nabla - 2.2) , \tag{3}$$

$$A_3 = 10^{(0.06V_c - 2.8)} , \tag{4}$$

Component A_1 represents the contribution by continental aerosols. AM is an air mass parameter that is allowed to range between integer values of 1 for open ocean and 10 for coastal areas and is given by

$$AM = INT(Rn/4) + 1 , \tag{5}$$

where Rn is the measured atmospheric radon content expressed in pCi/m. In the absence of radon measurements, the air mass factor can be related to the elapsed time, T(days) for the air mass to reach the point of observation:

$$AM = INT[9 \exp(-T/4)] + 1 \quad . \tag{6}$$

Components A_2 and A_3 represent equilibrium sea spray particles generated by the surface wind speed averaged over 24 hours (∇, in m/s) and the current surface wind speed (V_c in m/s), respectively. (It should be noted that the current wind speed component is different from the value published in LOWTRAN 6. This modification was found to be necessary (Wollenweber, 1988) to match previously published measurements of IR sky radiances and near surface aerosol size distributions (Hughes, 1987) using the model. In Equation (1), r_i, the modal radius for each component referenced to a relative humidity of 80% ($r_1 = 0.03\ \mu m$, $r_2 = 0.24\ \mu m$ and $r_3 = 2.0\ \mu m$) is allowed to grow with relative humidity (RH) according to the (Fitzgerald, 1975) formula

$$f = [(2 - RH/100)/6(1 - RH/100)]^{1/3} \quad . \tag{7}$$

The contribution to the total extinction or absorption by each component can then be written as

$$\sigma_{e,a}(\lambda)_i = (SF)\left\{C_i \int_r Q_{e,a}(\lambda, r, m) \exp\left[- (\ln \frac{r}{fr_i})^2 \right] r^2 dr \right\} , \tag{8}$$

where $C_i = (0.001\pi/f)A_i$. The factor f^{-1} in the expression for C_i ensures a constant total number of particles as the relative humidity increases. $Q_{e,a}(\lambda,r,m)$ is the cross section of the spherical particle, and m is the complex refractive index, which is allowed to change from that of dry sea salt as the particle deliquesces with increasing humidity. LOWTRAN 6 provides precalculated values in tabular form of the parameter $\sigma_{e,a}(\lambda_i)/C_i$ at discrete wavelengths for four relative humidities (50%, 85%, 90% and 99%), from which the average extinction for a specific wavelength band and relative humidity can be readily determined by interpolation. When an observed surface visibility (VIS_0) is available as an input to the model, the amplitudes of the three components are adjusted by a scaling factor (SF) so that the calculated aerosol extinction coefficient, σ_c, at a wavelength of 0.55 μm is the same as the observed extinction, σ_0, determined from the relationship

$$VIS_0 = \frac{3.912}{\sigma_0 + \sigma_r} \tag{9}$$

where σ_r is the Rayleigh contribution to extinction at 0.55 μm.